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**AN INTEGRATED VIEW OF WEB CONSOLIDATION PROCESSES**

**CLYDE H. SPRAGUE**

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**Clyde H. Sprague**

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**AN INTEGRATED VIEW OF WEB CONSOLIDATION PROCESSES**

**\*Clyde H. Sprague**  
Principal Research Engineer  
The Institute of Paper Chemistry  
Appleton, Wisconsin U.S.A.

**\*Now Associate Director**  
Pulp and Paper Technologies  
Mead Central Research  
Chillicothe, Ohio U.S.A.

## ABSTRACT

Historically, paper has been consolidated by wet pressing followed by drying on steam cylinders or by other low intensity evaporative processes. Although these time-tested processes will continue to be the mainstay of papermaking for some time, they are now being challenged by new systems that exploit the interactive effects of increased pressures and temperatures. We want to review our understanding of these hybrid processes and the unprecedented performance potential they offer. At the same time, we want to integrate them into a common context with the more conventional web consolidation processes. To do this, we define four classes of systems: mechanical, thermal, thermal with restraint, and thermomechanical. Each class uses mechanical, thermal, and interactive effects in a unique way to determine water removal rates, energy efficiency, property development potential, and machine size and complexity. In a parallel and unifying fashion, each class also occupies a distinct region on coordinates of specific energy consumption and working temperature. This diagram is offered as a starting point for integrating wet pressing, hot pressing, cylinder drying, press drying, Condebelt drying, impulse drying, and others into four distinct classes of web consolidation systems.

## INTRODUCTION

Historically, paper has been consolidated by wet pressing followed by drying on steam cylinders or by some other evaporative process. These basic processes have been thoroughly studied and are fairly well understood. A review of wet pressing and conventional cylinder drying will be presented in another paper in this symposium. They will be treated only very briefly in this paper and then only for the purposes of comparison and unification of the many web consolidation processes now under consideration.

Despite the venerability of wet pressing and conventional cylinder drying, they fall far short of satisfying the needs of the papermaker. As a result, a number of new web consolidation processes have been proposed or used in the last 25 years. These processes, at least the ones to be considered in this paper, combine the use of thermal energy, as delivered to the web by one or more hot surfaces, with pressures well above those typically used in thermally based systems.

These new consolidation systems divide naturally into two classes. In one class, water is still removed as vapor, but the rates are higher than typical and the property development potential is improved by both temperature and pressure effects. Thermal energy is still used in about the same amounts as in conventional cylinder dryers. The main new effects are elevated sheet temperatures and drying under z-direction restraint or compression. We elect to call these TZ systems as an abbreviation for thermal drying (evaporation) with z-direction restraint. To qualify for this class, the restraint must be sufficient to improve properties. Otherwise, the systems remain as thermal (T) systems. Examples include several early versions of so-called press dryers and thermal vacuum or Condebelt dryers.

Some of the new systems combine temperature, pressure, and an appropriate sheet moisture content with a mechanical configuration that can produce and exploit sheet saturation. Under these conditions, some new mechanisms come into play that greatly improve the speed and thermal efficiency of water removal and, at the same time, offer excellent property development potentials. These systems we elect to call thermomechanical web consolidation systems (TM) because they remove water by mechanical and thermal means, and by an

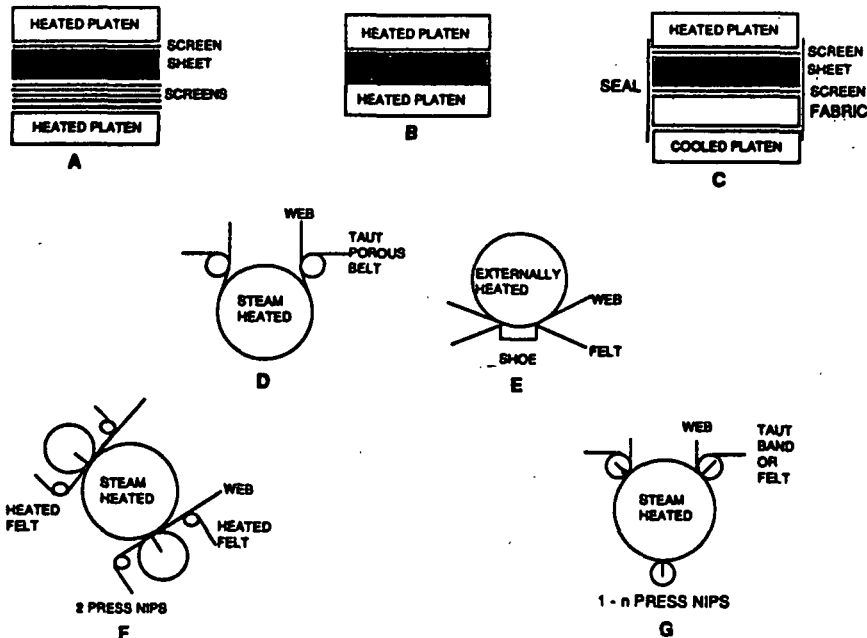
interactive combination of the two. Examples include many of the proposed or existing pilot configurations for press drying (18), and impulse drying. The thermodynamic behavior of the TM systems is unique among web consolidation systems and our understanding has been developed largely over the past 4 or 5 years.

The intent of this paper is twofold. First, we want to review some of the fundamentals of TZ and TM systems with special attention to the latter since they have been investigated most recently. Second, we want to examine a single unique diagram as a way of unifying our descriptions of all the common web consolidation processes. We start by reviewing some of the pioneering work, first on systems of the TZ class, and then on systems of the TM class. By dividing the review along these class lines, we will not be able to preserve chronological order. We will attempt to preserve time relationships by dating the various works, however.

#### **SOME PIONEERING TZ PROCESSES**

##### **Z-direction Restraint**

In 1975, Setterholm, et al. (1) examined the use of z-direction restraint in drying to improve paper properties. In a laboratory study, Douglas fir pulps from 49 to 62% yield were dried under either continuous or intermittent restraint. Restraint pressure was typically 400 kPa with platen temperatures at about 150°C. Apparently the pressing configuration was that described in a subsequent paper (2) as a heated platen, one 150 mesh screen, the sheet, five 150 mesh screens, and a second heated platen, Fig. 1A. These tests produced excellent density and physical properties, often far in excess of commercial practice. High strength from the highest yield furnish was a particularly noteworthy result. Several different cyclic applications of pressure, examined to test various possible implementation schemes, showed significant property development, as well.



### Press Drying

Two years later, Setterholm and Benson (2) described the results of "press drying" high yield hardwood pulps. This is the first mention of the term "press drying." In this study, the platen-sheet configuration was as described above, but most of the tests were conducted with a platen pressure of 2.8 MPa and a temperature of about 200°C. Excellent densification and strength properties were obtained by press drying these furnishes, showing the great potential of using such processes to produce good products from stiff furnishes. Completely drying the sheets from 30% solids required from 5 to 900 seconds for platen temperatures from 260°C down to 93°C and a platen pressure of 400 kPa. In subsequent tests with the same

or a similar apparatus, Byrd (3) showed sheet internal temperatures of about 100°C through the drying cycle. After drying, sensible heating raised the sheet temperature to near the platen temperature.

In an early examination of the role of fiber composition in press drying property development, Horn (4) studied pulps with a wide range of lignin and hemicellulose contents. These were dried from 60% solids, between screens at a pressure of 2.76 MPa and a temperature of 204°C. For this drying configuration and time, the web temperature should remain at 100°C while moist, and then climb to the platen temperature of 204°C when dry. Horn attributed the excellent strength of the press dried products solely to hemicellulose softening and flow which, under moist conditions, can occur at a temperature well below 100°C. Lignin, in contrast, softens at a temperature well above 100°C when moist and even higher when dry. Based on this, the low bonding potential of lignin, and the absence of any direct relationship between lignin content and observed strength, Horn concluded that lignin was not a factor in strength development. The press dried high lignin sheets also showed favorable creep rates, which Horn attributed to lignin protection of hydrogen bonds.

Byrd (5) extended Horn's study by press drying special pulps having independently controlled lignin and hemicellulose contents. He also used a much wider range of initial moisture contents. These sheets were also dried between screens. Byrd showed that sheets with a high hemicellulose content exhibited flow earlier and at a lower temperature, and that they produced higher adhesion strength. He also showed that lignin content had no effect on the hemicellulose softening temperature, as measured by the onset of interlaminar shear strength development. For his drying conditions, there was evidence of hemicellulose flow in about 1 second, whereas lignin required about 15 seconds. These are presumed to be related to sheet temperatures and polymer softening temperatures, and not to any particular time dependency of these softening processes. From these results, Byrd supported Horn's conclusion that hemicelluloses are responsible for strength, and that lignin serves only to delay flow of the hemicellulose and does not contribute to strength.



Byrd examined the wet strength of these sheets by soaking them either in water or in a weak sodium hydroxide solution, which preferentially attacks lignin bonds. Lignin-free pulps produced similar results in these two tests. For increasing lignin contents, the wet strength retention was greater under water soak conditions. Byrd attributed these results to latent lignin flow, which protects the hydrogen bonds from moisture attack. He further suggested that the exposure times were not sufficient to produce moisture resistance from auto-crosslinking in cellulose. Hence, Byrd supported Horn's contention that moisture resistance was due solely to lignin protection of hydrogen bonds. Back's view (6) is that moisture resistance is the result of auto-crosslinking, a process which requires hot-when-dry conditions and, depending on the treatment temperature, can be relatively slow.

In parallel but independent work, Anderson and Back (7) investigated a similar press drying process, prompted, in part, by his earlier work on hardboard. Kraft softwood pulps from 52 to 69% yield were dried between two polished and heated platens, Fig. 1B, maintained at temperatures up to 350°C for some of the experiments. In preliminary experiments at various pressures, Back found that the sheet temperature remained nearly constant at the saturation temperature corresponding to the applied pressure during the evaporative drying period. After drying, the temperatures climbed toward the platen temperature so these experiments also produced hot-when-dry conditions. Most of the actual drying experiments were carried out at a platen temperature of 200°C and an unspecified pressure.

Results were compared with liner made by conventional processes. Back also studied the effect of initial moisture content on property development. At 52% yield, press drying showed no advantage over conventional processes when compared at equal density, thus showing that high sheet temperatures did not produce any independent effect. Essentially equivalent results have been produced in impulse drying (8). At higher yields, Back's press drying results did show higher strengths at a given density. Here, the beneficial effects of sheet softening apparently came into play offsetting the normally detrimental effects of higher yield. At a platen temperature of 200°C, incremental performance gains from press drying began at about 50% moisture and increased with wetter sheets. At 350°C, benefits began at a slightly lower initial

moisture. There is no mention of the probable mechanism. Moisture resistance of the press dried sheets was not evaluated in this work.

In all of this early work on press drying, the sheets were overdried, i.e. they were left in the dryer long after reaching 93-94% solids, and most were fully restrained throughout the drying process. In such experiments, the temperature-when-dry will be near the platen temperature, i.e., in the 150-200°C range. In the Forest Products Laboratory experiments which sandwiched the sheet between screens, the temperature-when-moist will be about 100°C, which is well above the hemicellulose softening temperature and well below that for lignin. For Back's experiments, which used polished platens that effectively seal the sheet, the temperature-when-moist could be well above 100°C, how far depending on applied pressure which was not specified. Hence, in these experiments some lignin softening is at least possible. This could contribute to improved fiber flexibility and conformability, and may be the explanation for the high strength to density ratio for the press dried sheets.

All of the press drying experiments cited here involve purely evaporative water removal and will use nearly as much specific energy as a cylinder dryer. Because of the elevated restraint pressures, property development was much improved over other thermal consolidation systems. Hence, these press drying configurations belong to the TZ class.

#### **Thermal-vacuum or Condebelt Drying**

A very novel paper drying concept was proposed by Lehtinen (9) in 1980. In this well known concept, the drying configuration consists of a cooled metal plate or belt, a felt or other water receiver, the moist sheet, and a heated metal plate or belt, Fig. 1C. The assembly is sealed along the edges and air is partially removed from the sheet and felt before the process is started. Vapor forms in the sheet and flows to the cool surface where it condenses at the cool surface temperature and is collected in the fabric. Since this temperature can be quite low, a fairly strong partial vacuum is formed. This compresses the sandwich and provides good heat transfer. Because of the vacuum, drying can occur at quite low temperatures, allowing use of waste heat. Properties may suffer, however.

Drying rates are improved by the absence of air and the good heat transfer, and can be about ten times those in a cylinder dryer. Specific energy consumption will be about the same as for a cylinder dryer since all of the water must be evaporated. A more recent version of this process (10) proposes drying between continuous belts, both of which are temperature controlled. This permits applying a z-direction restraint, and adjusting the average sheet temperature and the temperature differential somewhat independently. In this way, it is possible to achieve sheet temperature and restraint conditions that are favorable for property development with stiff furnishes, as in press and impulse drying. This system, called a Condebelt dryer (11), is an elegant example of a system designed for property development. Because it is an evaporative dryer with sufficient restraint to improve properties, it is a TZ dryer.

#### **SOME PIONEERING PROCESSES OF THE TM CLASS**

##### **A Taut Belt-Steam Heated Cylinder System**

In a remarkable piece of work, documented in a rarely referenced patent (12), first applied for in 1963 and issued in 1967, Gottwald, et al. describe what appears to be the first "press dryer" for paper. Their invention was used on an operating paper machine to produce several grades by passing a moist web between a metal cylinder, internally heated with high pressure steam, and a taut porous fabric or belt. Fabric tensions are set to give normal pressures "of at least 35 kPa and greater than the vapor pressure of the liquid at the temperature employed." The recommended temperature range is from about 120 to 250°C. This version of the process is depicted in Fig. 1D.

Gottwald, et al. cite "drying" rates of about 220 kg/hr/sqm as compared to about 25 for cylinder drying. Of this amount, about half leaves the sheet as cool liquid, showing that it is true liquid dewatering and not condensed vapor. They also showed increases in web strength and stiffness with increasing belt tension, i.e., z-direction restraint. Dewatering was attributed to four factors: the driving force of vapor, pressing of the web, reduction of water viscosity, and flash evaporation. This is the first known suggestion of a vapor displacement or entrainment mechanism. A simple calculation, based on an example from the

patent, gives a specific energy consumption of about 1700 kJ/kg of water removed. This patent also mentions the "use of a series of dryers ahead of the press nip" as a sort of hot press.

### **Impulse Drying**

Wahren (13) pioneered the use of a press nip with one externally heated roll as a hybrid or thermomechanical web consolidation system, later named impulse drying (14). A patent, first applied for in 1978, was issued in 1982 (13). External heating and high surface temperatures were used to support the extremely high heat transfer rates in the nip needed for rapid water removal. Wahren claimed rapid generation of steam near the hot surface and significant liquid dewatering as a result. In a subsequent paper, Arenander and Wahren (14) call this the "steam pulse effect," a new mechanism which they believed was responsible for the extraordinary water removal rates, often as high as 30,000 kg/hr/sqm. Whether they believed the steam pulse effect caused displacement or entrainment, or both, is not clear. This would appear to be the same mechanism described by Gottwald and co-workers (12).

Using a roll press nip restricts contact time to a few milliseconds, but longer nip presses, Fig. 1E, can extend this. In either case, the process rates are very high because of the high temperatures and pressures involved. This would appear to be a high intensity version of the Gottwald, et al. (12) system, although the developments were apparently independent.

### **TEM-SEC or Direct Action Hot Pressing**

Another system of this general type is known as the TEM-SEC press or the Direct Action Hot Press (15,16). A large, central roll of a special material, heated internally with low pressure steam, serves as the common element of two successive press nips, each with its own felt which may also be heated, Fig. 1F. The unconstrained sheet follows the hot roll between nips. Sheet exit temperature is measured and used to control the temperature of the roll surface. The large common roll makes both nips somewhat longer than in a conventional roll press.

Although this system operates at low temperatures, the combination of heating from both sides of the sheet and intimate contact with the roll gives good heat transfer. Press exit dryness levels in the 52-58% range have been achieved in commercial practice over the last several years. Elevated sheet temperatures and corresponding reductions in water viscosity are cited as the basis for this excellent performance. Although this configuration is very similar to that of the impulse dryer due to Wahren, the conditions employed are very mild so vapor generation and vapor driven liquid dewatering are unlikely. Hence, this system probably belongs in the hot pressing class (mechanical web consolidation) and will not be discussed further in this paper. A modest increase in the intensity of the operating conditions could move it into the TM class, however, so it is mentioned here.

#### **Pilot Press Dryers**

The early press drying systems (1-5,7) invoked a purely evaporative mechanism to fully dry the sheet. As a result, they are fairly slow despite using quite high pressures. Commercial implementation of a system utilizing both a high pressure and a fairly long drying time is a serious challenge, as noted by Wedel (17). Because of this, most laboratories involved in press drying research proposed alternate configurations for pilot scale press dryers. Swenson (18) describes a number of these. In general, they all involve heated rolls and press nips or belts, or both to get the required constraint. At commercial speeds, most would provide only partial drying. Most also involve direct contact between the moist sheet and the heated surface on one side and some type of open mesh material on the other to either receive water or allow vapor to pass. All of these can be represented by various combinations of nips interspersed with taut belts, Fig. 1G.

#### **THE CLASSES OF WEB CONSOLIDATION SYSTEMS**

Wet presses and hot presses remove water by reducing the volume of the moist web and are thus mechanical web consolidation systems. Cylinder dryers and other low restraint evaporative systems are purely thermal systems. Our understanding of these types of systems is fairly well developed and will be described elsewhere in this symposium.

Adding an appreciable level of restraint to a thermal web consolidation system tends to raise the sheet temperature and the evaporation rate. The high web temperature and the increased z compression may improve properties, especially for stiff furnishes. The dewatering mechanisms in this subclass are not new, however. We will return to the TZ systems later when we consider unification.

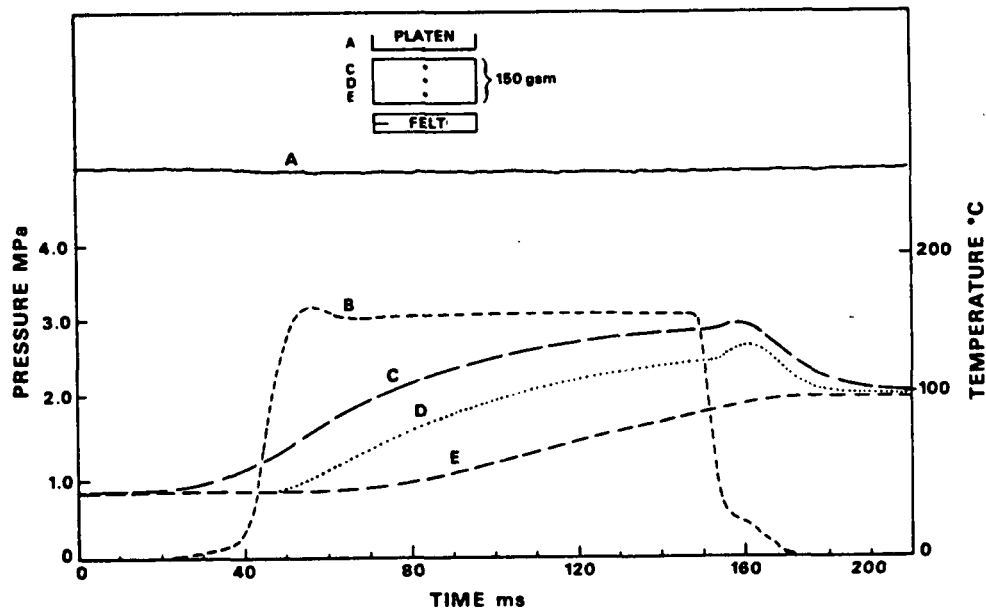
In contrast, thermomechanical web consolidation systems involve both new dewatering and new property development mechanisms. They are usually partial "dryers" in that appreciable water may remain in the sheet at the conclusion of the process. An understanding of the thermodynamics and fundamental mechanisms of these processes of web consolidation has been developed in the last few years and deserves our detailed attention before we proceed to unification.

For our purposes, these systems all sandwich the sheet between one heated surface (direct contact) and a porous member which acts to pass vapor or collect water. If the conditions are mild, such systems will act like a cylinder dryer. Moderately more intense conditions may produce the behavior of a restrained evaporative dryer or TZ systems. The process of real interest occurs, however, for higher pressures and/or wetter sheets, where saturation is likely. Under these conditions, very different mechanisms prevail. Mechanical configurations which can produce saturation include very taut porous belts, Fig. 1D, press nips, Fig. 1E, or combinations of nips and belts, Fig. 1G. Various combinations of these basic configurations can represent impulse drying, all of the pilot press dryer configurations described by Swenson (18) and, perhaps, others. These are the thermomechanical web consolidation systems. As we will show in the next section, the fundamental thermodynamics, water removal, and property development characteristics of these processes are very different from that of the other web consolidation processes of interest in this paper, including the TZ systems.

## THE MECHANISMS OF THERMOMECHANICAL WEB CONSOLIDATION SYSTEMS

### Wet Pressing in Thermomechanical Web Consolidation

When the sheet first contacts the hot surface in a thermomechanical consolidation system, the sheet temperature is raised by conduction and convection heat transfer (19) until vapor begins to form. During this vapor-free period, liquid dewatering by volume reduction, as in wet pressing, is possible if the pressure-time history and the sheet moisture content are sufficient to produce saturation. There may be some thermal augmentation (hot pressing) because of heating of the sheet. This should be a quite small factor, however, since the average sheet temperature rises only slightly in this period even though the temperature near the hot surface is approaching an elevated boiling temperature, Fig. 2.



Shortly after first contact, liquid near the hot surface will reach the saturation temperature corresponding to the local hydraulic pressure, and vapor will begin to form. By definition, wet pressing will cease since the sheet is no longer filled with liquid. However, vapor displacement of liquid water will begin at this time with an initial vapor pressure equal to the hydraulic pressure at the end of the wet pressing period. Up to this point, water removal by wet pressing should depend on the imposed pressure-time history in the usual fashion, altered slightly by increased web temperature. Conditions that promote rapid initiation of boiling will tend to shorten the wet pressing period and lengthen the vapor displacement period. Because the driving pressures and flow resistances for wet pressing and vapor displacement are equal at the transition point, the dewatering rates should be nearly the same, as well.

So far, there are no known ways of distinguishing the liquid dewatering from wet pressing and vapor displacement nor to detect the exact transition point. Hence, independent experiments (20,21,22), run with an unheated pressing surface, may overestimate the amount of water removed by volume reduction when the pressing surface is hot. It is expected that the wet pressing component will increase with increasing sheet moisture, increasing pressing pressure, decreasing surface temperature, and decreasing sheet flow resistance. According to heat flux data obtained by several authors (20,21,23), a rapid rise in pressure may promote earlier boiling, but how this trades off with a similar increase in wet pressing is unknown. Devlin showed about 9% water removal by independent wet pressing experiments. Because of the slow pressure rise and the intense heat transfer, it is possible that wet pressing was totally suppressed by early boiling in his subsequent drying experiments. This is consistent with instantaneous measurements which showed that the sheet just reached the saturation caliper when vapor displacement was believed to have started.

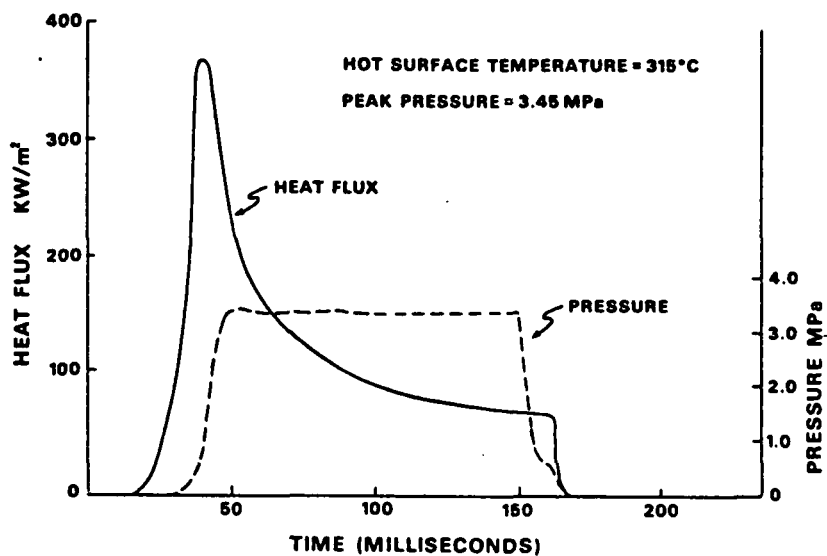
Water removal by wet pressing is likely in Configurations 1E, F, and G, but could also occur in Configurations 1C and D for very wet sheets and high levels of restraint. Liquid saturation is possible in Configurations 1A and B, but liquid dewatering is hindered by the absence of a transverse flow path. If liquid dewatering occurs, it must proceed from the outside of the sheet to the middle. This would also affect



heat transfer and the thermal effects, leading to strong in-plane gradients. In commercial systems of this type, which would require very large drying areas, the feasibility of in-plane liquid flow becomes even less. Configurations 1A, B, C, and D are likely to be largely evaporative dryers whereas Configurations 1E and G allow for the possibility of liquid water removal by wet pressing or vapor displacement or both. Evaporation of any kind is unlikely in the TEM-SEC press, Configuration 1F, because of the mild conditions used.

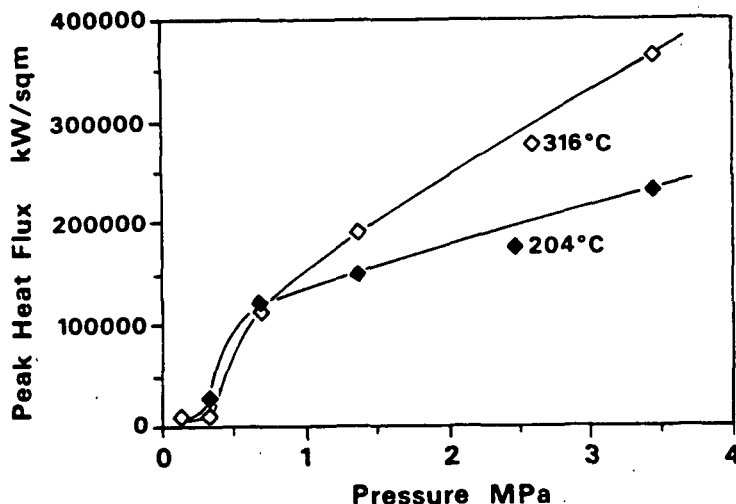
#### **Heat Transfer at the Sheet-Hot Surface Interface**

Heat transfer in TM processes can be very vigorous and may constitute the rate limiting factor for performance. It is strongly influenced in both character and level by the pressure-time history imposed on the sheet. Hence, let's examine the effect on heat transfer of several rectangular pressure pulses of various levels. If the pressure is increased fairly rapidly to values in the wet pressing range and held for even a few milliseconds, the heat flux behavior is dramatic, as shown in Fig. 3. The early, very large heat flux peak is characteristic. For haversine shaped pressure pulses, Burton (23) has recorded peak values up to 800 kW/sqm using a hammer and anvil wet press simulator; Lavery (21) and others have recorded values in excess of 300 kW/sqm under many conditions with electrohydraulic presses, which have a somewhat slower initial pressure rise. Lavery (21) has noted that these peak values decrease slightly with increasing initial sheet solids over the range from 20 to 50%. The heat flux peak usually occurs before the pressure peak, regardless of how short the pressure pulse or how fast the pressure rise. Hence, the pressure rise rate and the heat flux rise rate are closely related.



Devlin (20), Burton (23), Lavery (24), and others have suggested that pool boiling at the hot surface is responsible for these high heat transfer rates. Lavery (24) suggests that the rising part of the curve is controlled by the pressure and temperature available at the hot surface and liquid availability in the sheet. A peak is reached when the liquid supply becomes inadequate to fully satisfy the boiling potential at the hot surface. After this peak, heat flux values decline rapidly to values of around 80 kW/sqm in 100 ms or so. Even this value is too large to be explained by conduction (19) suggesting that boiling continues.

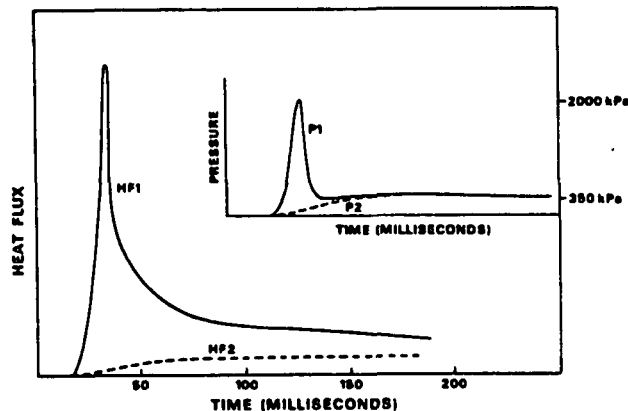
Peak heat flux values, obtained in similar experiments at successively lower pressures, show a type of threshold behavior, Fig. 4. Apparently, there is some minimum pressure necessary to initiate this type of boiling heat transfer. Two explanations are possible. If the pressure is low or the sheet relatively dry, liquid saturation and, hence, pool boiling may be precluded. Additionally, heat transfer may be limited by low contact pressures which may be further lowered by vapor pressure lift off. For these explanations, the threshold pressure should increase with initial sheet solids, lower sheet compressibility, and increasing hot surface temperature. There are no data with which to test these ideas, but independent experiments show that wet pressing becomes effective at about the same pressure as the threshold for high heat flux. Hence, saturation is probably necessary for high heat transfer rates. Later, we will show that rapid dewatering and property development are very dependent on these high heat flux values, as well.



For sheets that are extremely wet or for pressures that are very high, hydraulic pressures may be sufficient to suppress boiling, at least for a short time. Despite this possibility, Lavery (21) has shown nearly equivalent heat

transfer in sheets from 20 to 50% solids when consolidated at a peak pressure of 4.8 MPa and a hot surface temperature of 315°C. For temperatures from 200 to 350°C, the corresponding saturation pressures are from 1.55 to 16.5 MPa. Hence, significant delay of boiling by excess hydraulic pressure is unlikely except in cases of low temperatures and/or very wet sheets.

Fig. 5 shows two different pressure-time histories and the corresponding heat flux curves for otherwise identical situations. Pulse P1 could be generated by a press nip followed by a very taut belt as in Configuration 1G. In contrast, P2 could correspond to a taut belt only, Configuration 1D. Two things can be noted from these data. First, the press nip pressure pulse is sufficient to initiate a high heat flux, HF1, even though it is short. Second, the low pressure tail in P1 produced by the taut belt can sustain a high rate of heat transfer. For the low pressure system without the nip, P2, high heat fluxes, HF2, are never achieved. Apparently, the nip serves to saturate and consolidate the sheet to initiate the high rate of heat transfer. A low pressure level following this pulse can maintain the compressed state and support the high rate heat transfer processes but, when used alone, cannot initiate them. A system with a low pressure zone followed by a press nip may have less potential than the reverse configuration.



Other similar tests show, however, that a tail pressure of about 350 kPa sustains the high heat flux whereas a pressure of about 70 kPa does not. Hence, there must also be a threshold pressure associated with the heat flux maintenance process. If a second nip is added after the low pressure dwell, Fig. 1G, the very high heat flux values can be reestablished. Hence, successive nips interspersed with very taut belts can probably be quite effective. The ability to initiate and sustain high heat flux values may be the single most important factor in the performance potential of thermomechanical web consolidation processes. As we have seen, this can be done with very taut belts, press nips, nips and belts, and, perhaps, other mechanical configurations, as well. There appears to be a threshold pressure required to initiate the high rate processes and a second threshold pressure required to sustain them. However, a continuously high pressure level is not necessary to sustain high heat transfer rates, once they are established.

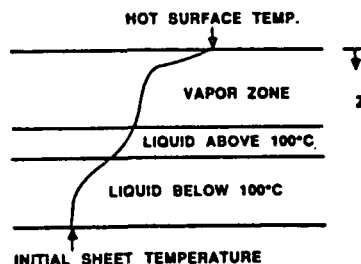
#### **Internal Heat Transfer and Vapor Displacement of Liquid**

For pressure and moisture levels sufficient to produce liquid saturation, several authors (19,20,23-26) have supported a two zone model to describe the internal thermodynamics. Vapor, formed at or near the hot surface, flows into the sheet under a total pressure gradient (because the sheet is initially saturated and air-free). When the vapor reaches a sufficiently cool zone, it condenses to raise the local temperature and redistribute the sheet water content. The cooler zone is liquid filled and forms a "seal" to prevent vapor flow from the sheet to the felt. This vapor-liquid interface is quite stable (19) so the sheet divides into a vapor zone next to the hot surface and a liquid-filled zone next to the water receiver.

Intense heat transfer, Fig. 3, forces the vapor zone to grow and the vapor pressure to increase under appropriate dynamic balance conditions. This leads to several important features of thermomechanical processes. First, the growing vapor layer "displaces" liquid water and serves as an effective dewatering mechanism. Again, numerous authors (19,20,23-26) have presented data and arguments to support the vapor-displacement mechanism. Recently, flash x-ray radiographs of an impulse drying event have provided strong visual evidence for the vapor front concept. Second, the

heat-pipe like heat transfer process, afforded by liquid reflux from the liquid pool back to the hot surface, quickly heats the sheet to quite high temperatures, Fig. 2. The elevated temperatures reduce water viscosity to aid liquid dewatering. They also soften fibers to improve compressibility and permit lignin and hemicellulose flow, an important factor in property development.

The sheet internal temperature data in Fig. 2 are typical and suggest the type of z-direction temperature distribution sketched in Fig. 6. Within the growing vapor zone, the temperature and pressure should be interrelated by saturation with only a small pressure drop to support vapor flow. Hence, the temperature through this zone should fall slowly toward the liquid zone. Devlin (20), and Sprague and Burton (25) have suggested that the liquid water bound to or in the fibers in the vapor zone will remain liquid because of hygroscopic effects. Hence, the fibers in the vapor zone remain hot and wet through much of the drying cycle, conditions that are ideal for web consolidation. The liquid pool is heated by conduction and convection heat transfer. Finally, liquid water is transported from the liquid pool to the hot surface by capillary action in the smaller pores. Because the temperature drop through the vapor zone is small, the vapor pressure drop opposing liquid reflux will be correspondingly small. Lindsay (26) has provided convincing theoretical and experimental evidence to support a reflux mechanism. He has shown that liquid reflux over only about 1% of the area in the plane of the sheet is sufficient to support the measured heat flux values.



As a specific example, Fig. 2, the vapor zone temperature may approach 150°C which has a corresponding vapor pressure of 460 kPa. This is the driving pressure for vapor displacement dewatering. This pressure will increase with hot surface temperature, if the applied pressure is sufficient to support it. At 460 kPa and 150°C, 0.0027 kg of water, evaporated at an energy cost of 5.7 kJ, can displace 1 kg of liquid water. Sensible heating requires a small additional amount of energy, but vapor displacement is an extremely energy efficient dewatering process. Thus, process conditions that emphasize vapor displacement will be most efficient.

The amount of vapor displacement dewatering depends on vapor-liquid interface penetration of the sheet. In time, the front will arrive at the sheet felt interface, giving the maximum possible vapor displacement dewatering. Since the felt permeability is high, the front temperature is assumed to be 100°C when it reaches the felt. The time required for the 100°C isotherm to reach the felt surface increases linearly with basis weight and decreases linearly with hot surface temperature, as shown by the regression coefficients below. The pressures used in these experiments, 2.1, 3.1, and 4.1, were not sufficiently important to be included in the equations. Front velocity is sensitive to furnish type, but not overly so, as these data show.

$$\text{Passage time (ms)} = A + B \cdot \text{Temp (}^{\circ}\text{C)} + C \cdot \text{BW (gsm)}$$

<u>Furnish</u>	<u>CSF (ml)</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>Corr. Coe.</u>
1	660	83	-0.30	0.68	0.83
2	660	105	-0.42	0.86	0.84
3	460	73	-0.25	0.62	0.94
4	300	80	-0.41	1.16	0.93

#### FURNISH DEFINITIONS

- 1 Unbleached Southern Pine Kraft at about 51% yield
- 2 Unbleached Red Oak Kraft at 59% yield
- 3 Bleached Kraft, 80% Eucalyptus, 20% Softwood
- 4 Same as 3 except refined in a Valley Beater to freeness shown

Vapor displacement, as described above, requires sheet saturation soon after contact with the hot surface. In some cases, the sheet may approach but not reach a saturated state. Evaporation near the hot surface, fed by capillary reflux, will cause condensation within the web and a corresponding redistribution of the sheet water (20). If this process is vigorous, enough water may concentrate at some zone in the sheet to cause local saturation. Vapor displacement would then proceed much as described for the saturated case. In fact, Lindsay's analysis (26) shows that conditions quite far from full saturation are still very favorable for liquid dewatering by a moving vapor front because of the widely different relative permeabilities of the gas and liquid phases. This may have been the operative mechanism in the Gottwald, et al. (12) dryer since significant liquid dewatering was observed, but the conditions used may not have produced sheet saturation by compression. This may also explain liquid dewatering from an initial solids of 65% in Lavery's (27) results where, again, saturation by sheet compression (as in wet pressing) is very unlikely.

#### **Flash Evaporation**

In the two zone model, the vapor zone is "sealed" from the atmosphere by the liquid saturated zone so that an appreciable vapor pressure can be generated. Liquid remaining with the fibers in this zone will be superheated with respect to the atmosphere, but subcooled with respect to the local bulk conditions because of hygroscopic effects. In the liquid zone there will be a thin "layer" of water next to the vapor zone that is above 100°C and, hence, superheated with respect to the atmosphere, Fig. 6. These conditions will persist until the vapor pressure falls below the local saturation pressure. When this occurs, flash evaporation will begin.

The vapor pressure may drop for either of at least two reasons. First, as suggested by Devlin (20), when the vapor-liquid interface reaches the sheet-felt interface, the liquid seal needed to maintain the vapor pressure will be broken. This may be a gradual process that commences when the front nears the felt. Also, there may be viscous fingering (19) of the vapor through the liquid when the liquid layer becomes thin. Any of these events would tend to lower the vapor pressure and initiate flash evaporation.



Second, in short duration processes, the applied pressure may be removed long before the front passes completely through the sheet. Here, too, the vapor pressure will tend to drop, as suggested by Burton (23), because it cannot be supported by the reduced applied pressure and the correspondingly reduced heat transfer. As suggested by Sprague (33), flashing during a period of declining applied pressure should continue to drive vapor displacement and to heat the remainder of the sheet. Once constraint is totally lost, however, there is no mechanism to support continued vapor displacement dewatering.

As the vapor pressure drops, hot water in the sheet will begin to flash into vapor. This should occur first in the boundary of the liquid pool next to the vapor zone where a very slight vapor pressure drop will initiate flashing. Flashing tends to sustain the vapor pressure so a dynamic balance condition should control the flashing rate. Flashing of water bound to or in the fibers will require a larger pressure drop because of hygroscopic effects. Hence, one would expect water to flash from progressively smaller pores as the flashing process continues. Under some conditions, the flashing process can become quite violent, leading to a sheet disruption process called delamination. This undesirable phenomenon has been described or alluded to by several authors (1,7,18,28).

Flashing tends to cool these two sheet zones quite rapidly (20,23,24). At the same time, the subcooled portion of the liquid zone is heated so that the entire sheet approaches a uniform temperature of 100°C immediately after the pressure is completely removed, Fig. 2. As a result, evaporation can continue for a short time after the pressure is completely removed to account for a small amount of water removal.

#### **SUMMARY OF DEWATERING MECHANISMS IN TM SYSTEMS**

If the applied pressure-sheet moisture content combination exceeds a threshold condition, the sheet will become saturated. Under such conditions, water may be removed early in the event by volume reduction, as in wet pressing. During this period, heat transferred to the sheet by conduction will raise the local web temperature to the saturation temperature corresponding to the local hydraulic pressure. At this point, the heat transfer mechanism changes to pool boiling, a vapor

zone is formed next to the hot surface, and wet pressing ceases. Liquid dewatering continues, however, as the high heat flux at the hot surface supports a growing vapor layer and a vapor-displacement-of-liquid mechanism. This divides the sheet into three thermodynamic zones as shown in Fig. 6. Proceeding from the hot surface, these are: a zone where the interstices are filled with vapor but the water in and on the fibers remains liquid because of hygroscopic effects; a zone filled with liquid superheated with respect to the atmosphere (above 100°C); and a zone filled with liquid below 100°C.

Vapor displacement continues until the vapor pressure in the vapor zone drops. This may occur when this zone has completely filled the sheet or when the external pressure is reduced, either of which will initiate flash evaporation of the liquid remaining in the sheet. Flashing initiated when the sheet still contains three distinct zones will promote continued vapor displacement of water and heating of the third zone. This process may be uncontrollable, however, leading to a violent release of energy and consequent damage of the sheet. Flash evaporation, initiated when the vapor front reaches the felt, will have mostly bound water to remove, a process that is likely to be gentle and nondisruptive. In either case, some water is removed as vapor by this flashing process. Some evaporation may also occur after the sheet leaves the "dryer," since the average sheet temperature is likely to be near 100°C.

Throughout much of the process, the fibers in the sheet are wet, hot, and under considerable structural load. These conditions, which are ideal for web consolidation, will propagate through the sheet as the process continues. Simultaneously, water is being removed from the web to promote hydrogen bonding. Because the sheet is hot and moist, lignin flow is also possible. Hence, based on these thermodynamic considerations, the TM processes would be expected to have considerable property development potential. This is indeed the case, as will be developed below. It should be noted, however, that these processes are normally interrupted before they can go to completion. This may leave significant z-direction gradients in the sheet. These can be alleviated, to some extent, by conducting a part of the drying from each side of the sheet.

All of these thermomechanical processes will revert to thermal web consolidation if the pressure falls below the maintenance threshold. A subsequent recompression of sufficient magnitude will restore the high rate mechanisms (thermomechanical processes), given appropriate sheet conditions.

As with conventional paper web consolidation processes, property development in thermomechanical web consolidation is not fully understood nor predictable in a quantitative sense. In general, however, these systems can produce two major strength development benefits: substantially increased densification and bonding, and moisture resistance. Under some operating conditions and for some furnishes, they may also produce higher strength at a given density than conventional processes. Although such processes also have an ability to influence surface and optical properties, these will not be discussed in this paper.

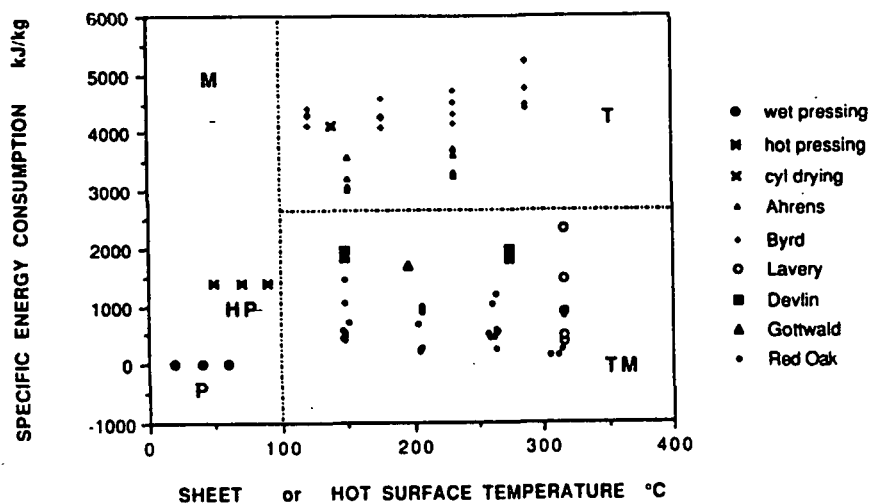
#### **A GENERAL WEB CONSOLIDATION DIAGRAM**

We now want to examine a way of unifying the whole family of web consolidation processes so they can be represented, in a useful way, on one major diagram. To do this, we introduce the idea of specific energy consumption. This is the amount of energy used for each unit of water removed in the web consolidation process, whatever it may be. Energy losses, that is, the efficiency of energy use from a machinery point of view, will not be of concern, for the moment. On this diagram, we want to examine energy efficiency, water removal rates or dewatering times, and property development.

#### **Wet Pressing**

Since a wet press does not use any externally added thermal energy, yet removes a great deal of water, the specific energy consumption is obviously zero. On coordinates of specific energy consumption versus web temperature, wet pressing is a single line, labelled P in Fig. 7. It is a line rather than a point because the web temperature may vary considerably, but will always be less than 100°C. Density will usually be well related to the press exit solids so more pressing, followed by conventional drying, produces higher

density. Bonding at the usual press exit solids levels is not sufficient to prevent springback of stiff furnishes, so these tend to produce lower densities. Hence, conventional wet pressing does not allow the use of some furnishes of interest.



### Hot Pressing

In hot pressing, thermal energy is added directly to the open web, usually with steam or infrared heating. Web temperatures are limited to less than 100°C since the web is not sealed to permit elevated vapor pressures. A simple energy balance, based on reasonable assumptions and well known rules of thumb (29), shows that the incremental water removal derived from web heating requires a specific energy consumption of about 1400 kJ/kg. On the diagram in Fig. 7, the line marked HP represents hot pressing over the normal web temperature range. Relative to wet pressing, the elevated web

temperature of hot pressing gives higher exit solids. There may be some independent increase in density with temperature, especially for stiff furnishes, as explained by Back (30). Hence, hot pressing is of value in reducing the load on the dryer section and may offer a limited way to extend the utilization of stiff furnishes.

Wet pressing and hot pressing are mechanical web consolidation processes where water is removed by volume reduction. The major effects of elevated temperature are greater water removal through water viscosity reduction and, perhaps, a slight improvement in fiber conformability. Unless carried to extreme levels of pressing with hot webs (31), these processes are limited to solids levels in the low 50% range and to densities of the order of 0.7 g/cc, even for flexible fibers. Temperatures and bonding cannot be raised sufficiently to have any significant independent impact on moisture resistance.

#### **Evaporative Drying**

For most other web consolidation systems of interest in this paper, hot surface temperature is a variable of great importance. It will usually range above 100°C. Hence, to represent such systems on the specific energy diagram, we change the abscissa above 100°C to machine surface temperature. In evaporative drying, we must supply sensible heating of the entire web plus latent heating of the water evaporated. This requires a minimum of about 2700 kJ/kg but, due to thermal inefficiencies, will usually require much more. On this augmented coordinate system, evaporative drying can fall anywhere in the region labelled T for thermal consolidation. Higher surface temperatures and contact pressures increase the heat transfer coefficients and the evaporation rates, but do not significantly change the energy efficiency.

Despite the commonality of water removal mechanisms and energy efficiency of evaporative systems, there are important distinctions in property development. Under low z-pressure conditions, bonding and fiber conformability in evaporative drying are dependent on the auto-contraction forces of drying. For flexible furnishes, these are sufficient to produce good bonding and correspondingly good strength properties. For stiff furnishes, however, these forces are inadequate to produce good consolidation. The resulting papers are poorly

bonded and have equally poor mechanical properties. As noted earlier, this has led to the consideration of the TZ systems which use higher pressures and somewhat altered drying configurations, especially for the stiff furnishes. The low pressure thermal web consolidation processes (T) are exemplified by cylinder drying as denoted by a total energy consumption example point in the diagram of Fig. 7. For the higher pressure TZ systems, we need to consider several specific examples for placement on this diagram.

Ahrens (32) examined the influence of hot surface temperatures up to 303°C and pressures up to 30 kPa on hot surface drying in a simulated extension of cylinder drying-like systems. In these experiments, the sheet was sandwiched between an impervious hot surface and a felt. At the highest temperature and pressure, the drying rate was about 4 times that for normal cylinder drying conditions. Properties and specific energy consumption were unaffected by conditions over these ranges. Specific energy consumption, based on energy delivery to the sheet from Ahrens data, are shown in the thermal region of Fig. 7. In later experiments, Ahrens extended the pressure range up to 350 kPa without altering the specific energy consumption. Unfortunately, property data for these higher pressures were not reported. In a further extension of this work, Devlin (20) showed that pressures above 2.1 MPa had a marked influence on water removal mechanisms, energy efficiency, and property development. Hence, there appears to be threshold pressure which can move these processes out of the thermal regime into the thermomechanical regime. Devlin's data will be discussed further below.

Byrd (3) dried linerboard sheets of about 200 gsm in a system like that in Fig. 1A, i.e., between screens that allowed easy vapor escape. Pressures of 14, 410, and 2760 kPa and temperatures of 121, 177, 232, and 288°C were used. Only the data for drying from 60 to 80% solids with two heated platens will be presented. Byrd's measured heat transfer data, divided by total water removal to get specific energy consumption, are plotted in Fig. 7. Whether Byrd's data are for energy transfer to the sheet only or include losses is not clear, but the numbers suggest the latter. In any event, specific energy consumption in this configuration is about 4500 kJ/kg and is only weakly dependent on drying conditions. Byrd also found that the mid-sheet temperature remained at about 100°C until the sheets were quite dry, and then climbed toward

the platen temperature. These results strongly support the notion that this is strictly a thermal web consolidation process with no liquid dewatering. Byrd did not present any property data in this paper, but very similar experiments with Douglas fir (1) produced densities of about 1.0 g/cc and excellent strength properties.

Anderson and Back's experiments (7) with two heated platens resulted in densities as high as 1.0 g/cc and correspondingly good physical properties. In the Condebelt dryer (9) density and strength increase with z-pressure up to about 0.4 MPa, and then level off. This level of restraint is lower than that used in most early press dryers (1-5,7). In a study of several softwood pulps, produced in several different ways, Michel and his colleagues found density to increase fairly rapidly with pressure at first and then level off for higher pressures. Although not sharply defined, this boundary was also at about 0.4 MPa. For evaporative press drying, it appears that density increases with restraint pressure up to a threshold value. This threshold is probably sensitive to pulp type, dryer type, and drying conditions such as temperature and sheet moisture content. Beyond this threshold, pressure does not seem to be very important to property development.

From these various experiments, we have to conclude that specific energy consumption will be about the same for all drying configurations that involve only evaporative water removal. Property development, on the other hand, can be improved as pressures and temperatures are increased from those used in cylinder dryers. Drying configuration may also be important. All of the TZ dryers can produce hot-when-moist conditions, but the Back double platen configuration or the Condebelt dryer may produce the highest internal temperatures. This would favor lignin softening and, in turn, could improve property development, especially of stiff furnishes. Back (6) has suggested the need to mechanically seal the back side of the sheet for some part of the drying time to achieve still higher temperatures and more lignin softening. In all TZ systems, the drying rates are restricted to values about 10 times those for a cylinder dryer. Hence, the dryer part will still be quite large.

### Thermomechanical Web Consolidation

As discussed above, the thermomechanical processes remove some water mechanically (wet pressing), some by evaporation (thermal), and some by vapor displacement. Because of liquid dewatering, these processes use much less energy than pure thermal dewatering. Hence, they all have specific energy consumption values in the region labelled TM (thermomechanical consolidation) in Fig 7. The relative contributions of the three water removal mechanisms determine where they fit on the diagram and, to a considerable extent, the property development potential of the process. These, in turn, depend on the particular conditions of temperature, pressure, and time used in drying.

Lavery (27) examined the drying behavior of 127 gsm linerboard sheets under conditions representative of the process called impulse drying, Fig. 1E. A haversine pressure pulse with a duration of 30 ms, a peak height of 4.8 MPa, and a platen temperature of 315°C were used on sheets with initial solids from 20 to 70%. For these experiments, specific energy consumption reached a minimum value of about 370 kJ/kg at an initial solids of 30% and a maximum of 2300 kJ/kg at 70% initial solids. These data clearly put impulse drying in the thermomechanical web consolidation regime, as indicated in Fig. 7, although the specific location will change as the impulse drying conditions change. For drying systems and conditions of this type, Lavery (8) has shown that density is primarily a linear function of the solids at the dryer exit. He has further shown that this relationship is not very sensitive to drying conditions, initial solids levels, basis weight, or whether the drying is done on one or two sides (i.e., with restraint lost between drying events). Similar data have been obtained for several very different furnishes. In some lower pressure experiments, there was an independent effect of pressure on density, as for the TZ systems.

Devlin (20) conducted some very thoroughly characterized experiments with a heated platen version of Fig. 1E. The sheets were removed from the dryer when they reached about 94% solids, i.e., when they were dry. He used 205 gsm linerboard sheets with an initial solids of about 42% and a four point plan with temperatures of 149 and 274°C, and pressures of 2.8 and 4.8 MPa. In all cases, liquid dewatering was near 30% of the total water removed. He also measured the water removed



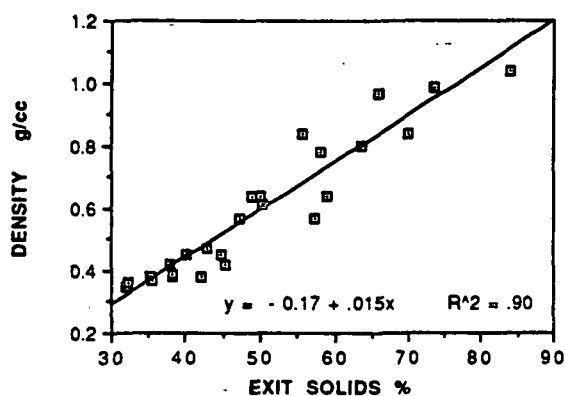
by pressing under the same conditions with a room temperature platen and found it to vary up to 9% of the total water removed. As noted before, however, such experiments may overestimate the volume reduction dewatering that occurs when the platen is heated. He found drying times of 1 and .4 seconds for the high and low temperatures, respectively, largely independent of pressure. He also found that the specific energy consumption values were nearly constant at about 1900 kJ/kg, independent of both pressure and temperature. This is consistent with a constant liquid dewatering fraction. These data, shown on Fig. 7, fall in the upper part of the TMC zone.

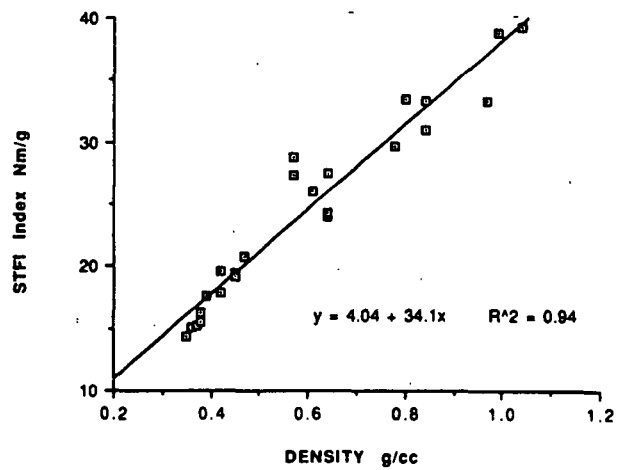
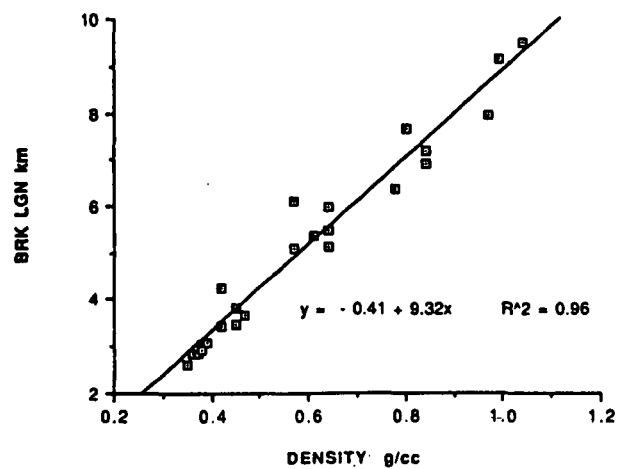
The work of Gottwald, et al. (12) for the drying configuration in Fig. 1D has already been described. The specific energy consumption is estimated to be about 1700kJ/kg, as shown on Fig. 7. They indicated an increase in strength and stiffness with increasing belt tension. This is in accord with the notion that pressure is an important independent variable when it is low.

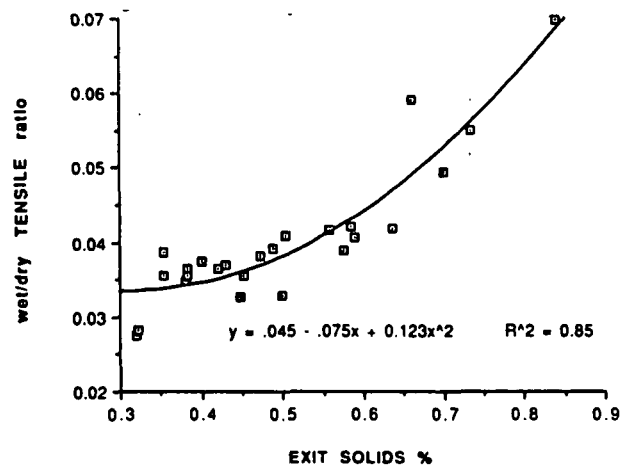
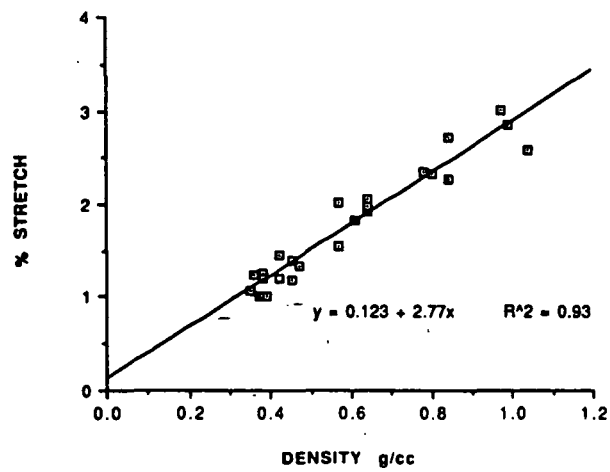
Many of the thermomechanical web consolidation experiments have not included energy measurement. This is especially true of those involving press nips and or taut belts and, hence, partial dewatering. This has left important parts of the TM zone devoid of data. To fill this in, some recent experiments were conducted with 100 gsm handsheets of high yield (59%) kraft red oak, pressed to an initial solids of 30%. Tests were conducted at platen temperatures of 149, 204, 260, and 316°C; constant pressures of 138, 345, 690, 1380, and 3450 kPa; and a nip residence time of about 100 ms, as would be produced by systems 1D or E. In these experiments, exit solids ranged from about 32% to as high as 85%. Only those experiments producing exit solids above 40% are included as having provided meaningful water removal. These tests gave specific energy consumption values up to about 1500 kJ/kg and are shown in Fig. 7.

Since these experiments provide specific energy consumption values that range over a large part of the TM zone, we elect to give a more detailed accounting of property development. In all cases, these were partial drying experiments, with final drying on a cylinder dryer simulator. The question to be examined here is how properties depend on the thermodynamics of the particular drying situation.

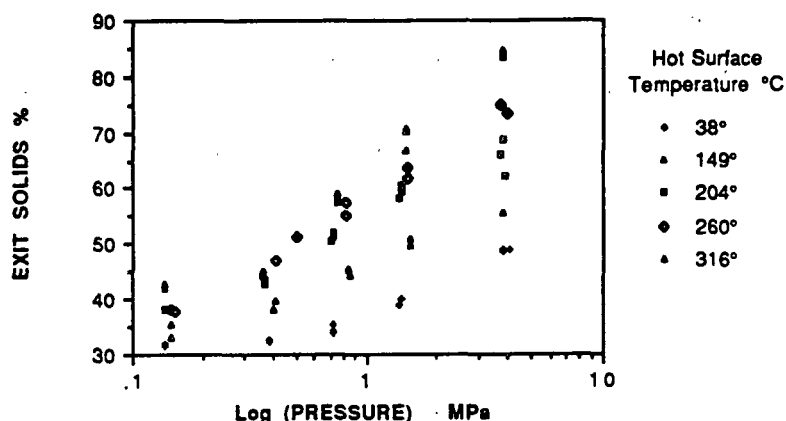
Density as a function of solids out of the dryer is shown in Fig. 8. Clearly, density is determined primarily by the amount of drying and not by the particular drying conditions, at least over this parameter range. Of particular note is the continuing increase in density with solids in the 85% solids range. Figs. 9-11 show that breaking length, compressive strength index, and stretch are linearly related to density. Breaking lengths of almost 10 km, compressive strength indices of nearly 40 Nm/g and stretch values of 3% are quite remarkable for this furnish. Finally, the ratio of wet to dry tensile strength improves directly with density, Fig. 12, although the relationship is not linear.



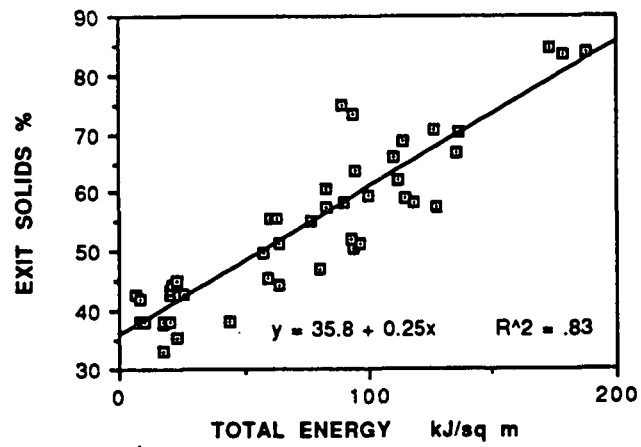
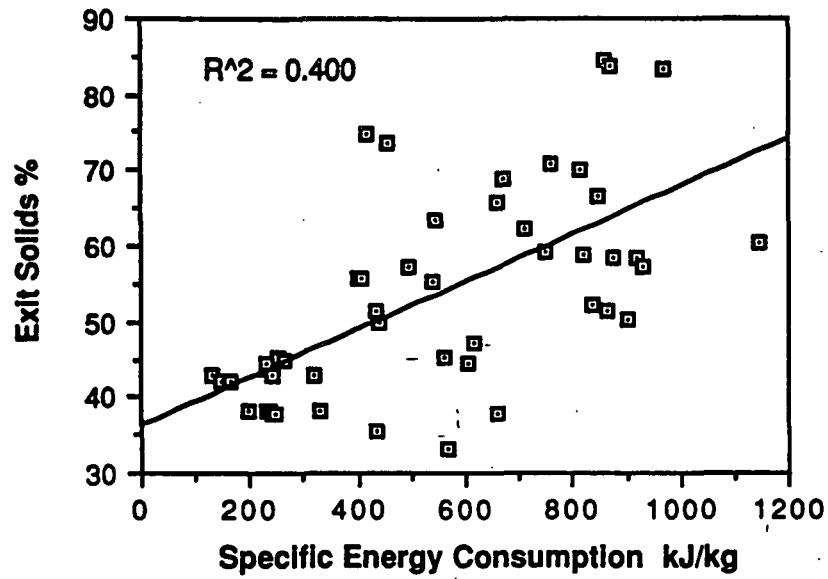




Since density is well related to exit solids and properties, in turn, are well related to density, it is important to relate the degree of dryness to the thermodynamic conditions used in the dryer. Fig. 13, for example, shows that pressure becomes important only when it exceeds a threshold value, as discussed before. Above this threshold, it is only mildly important, but becomes more so as hot surface temperature is increased. Temperature is very important, however, regardless of pressure. For these processes, density (solids out) and the average sheet temperature-time exposure increase together. The resulting increased thermal effect may be responsible for the improved moisture resistance. Auto-crosslinking is unlikely since these processes never produce hot-dry conditions unless carried to extremes.



If we relate dryness gains to the specific energy consumption, we find a positive trend, but the relationship is poorly defined with a correlation coefficient of only 0.4, Fig. 14. This clearly shows that specific energy use alone does not determine dryness or density. Dryness shows a much stronger relationship to the total energy transferred during the drying event, Fig. 15. Hence, as noted before, the heat transfer rate at the hot surface is a primary rate limiting factor.



There are several remarkable performance features of the TM systems. They offer an excellent ability to produce dryness, density, and strength at pressures and temperatures near those used in TZ systems. The required time interval is usually much less, however. When compared with wet or hot presses, or low pressure thermal systems, the TZ and TM systems offer vastly improved dewatering and property development potentials.

#### **SUMMARY**

Most of the important web consolidation systems either in use or proposed have been represented on a single coordinate system of specific energy consumption versus either web or hot surface temperature, Fig. 7. On these coordinates, the most important web consolidation processes divide into three classes, each represented by a different area on the diagram.

Processes in the mechanical zone (wet and hot pressing) are very fast and use little thermal energy. However, they have limited property development potential, especially with stiff furnishes. Exit solids are limited to around 50% unless extraordinary levels of hot pressing are used.

Processes in the thermal zone (T systems such as cylinder dryers) are slow and energy intensive. If the constraint pressure is low, they also have limited property development potential. In contrast, systems with higher levels of constraint (TZ systems such as the platen press dryers and the Condebelt system) can be much faster and produce much better properties, even with stiff furnishes. Commercial TZ systems will still be quite large and operate at a substantial pressure. Hence, their design will be a challenge.

Processes in the thermomechanical zone (TM systems such as the impulse dryer and several of the proposed press drying pilot configurations) will remove liquid water by wet pressing and vapor displacement. Evaporation will remove some additional water. These systems can be very fast and, hence, quite small. They will usually leave some water in the sheet to be removed by other dryers. They can be very energy efficient and have an excellent property development ability, usually in proportion to the amount of drying that is accomplished. Dewatering and property development relate poorly to energy efficiency, but relatively well to total

energy transfer. Hence, heat transfer from the hot surface to the sheet is the rate limiting step in such processes. Hot surface temperature is a very important variable; pressure is much less important provided it is above a threshold value. Because these processes are intense and short, they induce strong gradients in the sheet which may remain at the conclusion of the process. The significance of this is not fully known, but can lead to such undesirable effects as sheet delamination or two-sided properties.

Assignment of a particular web consolidation process to one of these classes depends on the conditions of the sheet, the drying configuration, and the drying parameters imposed. Once assigned to a class, location of the process on the specific energy diagram is relatively straightforward. This location, in turn, determines the mechanisms of the process and much about its performance potential. Hopefully, the terminology adopted for this diagram and the use of the diagram will help in the development and communication of understanding of all these important web consolidation systems.

#### ACKNOWLEDGEMENT

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- Fig. 1. Mechanical configurations for various hybrid dryers. A, B and C are constrained evaporative dryers (TZ). F is a TEM-SEC press. D, E and G can all be thermomechanical web consolidation systems (TM).
- Fig. 2. Internal temperature measurements in impulse drying. A is the platen temperature, B is the applied pressure, and C, D, and E are temperatures at 50, 100, and 150 gsm from the hot surface, respectively. Total sheet weight was 150 gsm.
- Fig. 3. Typical pressure and heat flux curves for thermomechanical web consolidation.
- Fig. 4. The effect of pressure and temperature on peak heat flux. Note the threshold at a pressure of about 0.4 MPa.
- Fig. 5. The effect of an initial press nip on heat transfer in a belt-type thermo-mechanical web consolidation system.
- Fig. 6. A sketched representation of the expected temperature distribution in a saturated sheet subjected to thermomechanical consolidation.
- Fig. 7. Specific energy consumption versus sheet or hot surface temperature for several different web consolidation configurations. Included are pressing, hot pressing, cylinder drying, high pressure cylinder drying (Ahrens), evaporative press drying (Byrd), and several versions of thermomechanical consolidation systems.
- Fig. 8. Density development with exit solids for thermomechanical consolidation of 59% yield kraft red oak at several different temperatures and pressures. Nip residence time was near 100 ms for all tests.
- Fig. 9. Breaking length versus density for the red oak tests described in Fig. 8.
- Fig. 10. Compressive strength index (STFI) for the red oak tests described in Fig. 8.

- Fig. 11. Stretch versus density for the red oak tests described in Fig. 8.
- Fig. 12. Wet to dry tensile strength ratios versus exit solids for the red oak tests described in Fig. 8.
- Fig. 13. Exit solids versus the log of pressure with hot surface temperature as a parameter. These data are from the red oak experiments described in Fig. 8.
- Fig. 14. Exit solids versus specific energy consumption for the red oak tests described in Fig. 8. As shown, specific energy is not well related to the dryness achieved.
- Fig. 15. Exit solids versus total energy transfer for the red oak tests described in Fig. 8.